EFFECT OF INNER LEAN ANGLE OF ARCH RIB ON SEISMIC PERFORM -ANCE OF DECK STEEL ARCH BRIDGE

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Abstract

The deck steel arch bridge is a common structure in mountain areas, so the study of its seismic performance is necessary. In this paper, the effect of inner lean angle of arch rib on seismic performance of deck steel arch bridge are investigated under various seismic excitation which is caused by longitudinal, transverse, vertical and combined direction strong ground motion. Four finite element (FE) models based on a typical deck steel arch bridge are established by using ABAQUS software. The total length of the typical deck steel arch bridge is 280m, and span and height of the arch rib is 210m and 21m, respectively. The seismic wave record which is obtained from the 1995 Kobe earthquake, JRT-NS, is inputted in the each FE model. Inner lean angle as variable are 0˚, 4˚, 8˚, 12˚, respectively. In this study, the arch rib, girder, side pier and column are modeled by the Timoshenko beam element which can consider shear deformation, and the reinforced concrete deck is modeled by three-dimensional shell element. The FE analytical results show that under the transverse excitation, for four inner lean angle which are selected in this paper, the maximum lateral responsive displacement is caused the arch bridge with inner lean angle 0˚, and the minimum lateral responsive displacement is caused the arch bridge with inner lean angle 12˚. Increasing the inner lean angle can improve the lateral stiffness of the arch bridge. The influences of inner lean angle of arch rib on the longitudinal excitation of arch bridge is small. Vertical seismic excitation have a great influence on the force and displacement response of the deck steel arch bridges. Under the combined seismic excitation, both the vertical displacement of the arch vault and the axial force of the arch foot are larger than only the case of longitudinal seismic excitation or transverse seismic excitation. Therefore, vertical seismic excitation should be considered in seismic designing for such arch bridges.

Keywords: bridge engineering, inner lean angle of arch rib, deck steel arch bridge, seismic performance, seismic excitation.

1. Introduction

With the bridge span increasing, steel arch bridge with the advantage of light weight and large span capacity are more and more used in bridge construction, in which the deck steel arch bridge is widely used in mountain area. The inner lean angle of the arch rib is a significant design parameter for arch bridge, which has great influence on the seismic performance. So the inner lean angle should be paid enough attention in the design of arch bridge.

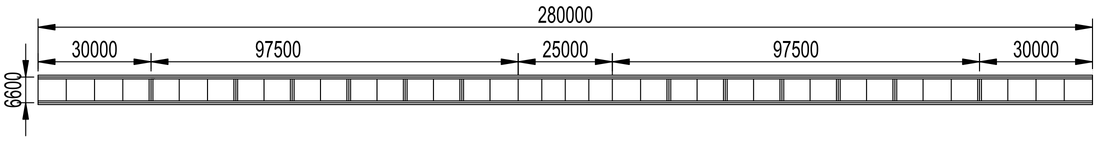
In recent years, Earthquake disasters have brought serious loss to people's production and life[1-2]. The bridge, as a significant infrastructure, should be guaranteed that it will not suffer serious damage under ground motions[1-2]. The steel arch bridge built in the mountain area is often the traffic artery crossing the canyon and river, which play an irreplaceable role to people along the mountain area. Therefore, the seismic performance of the steel arch bridge under strong ground motions should be specially studied[3-4].

At present, researcher at home and abroad mostly have studied the influence of external factors on the seismic performance of steel arch bridges. However, the influence of inner lean angle on the seismic performance and seismic response of steel arch bridges under the vertical ground motion are rarely studied. In this paper, 3-D finite element models of deck steel arch bridge, which inner lean angle of arch rib is 0˚, 4˚, 8˚, 12˚, are established by the ABAQUS package, respectively. The seismic performances of the deck steel arch bridge are investigated under various seismic excitations, which can provide reference in seismic design and engineering practice of deck-type steel arch bridge.

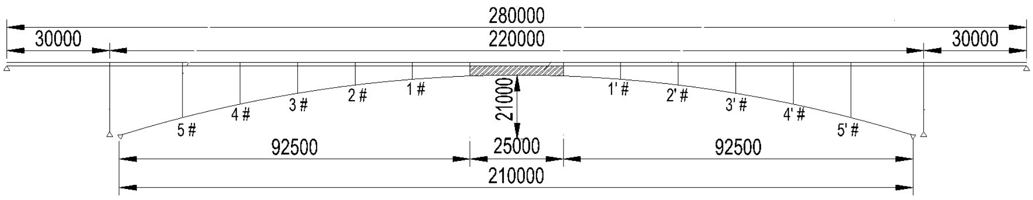
2. Bridge profile and establishment of finite element model

2.1 Bridge profile

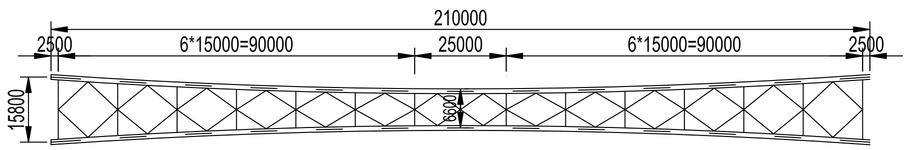
The bridge in this paper is based on a practical deck steel arch bridge[5]. The total length of the bridge is 280m, in which the calculated span and calculated height are 210m and 21m respectively, and the rise-span ratio is 1/10. The inner lean angle of the arch rib is 12˚, and the arch axis is quadratic curve. The distance between of the two girders is 6.6m. The full width of the bridge is 12m. The bridge deck is composed of reinforced concrete with width of 12m and thickness of 0.27m. The in-site is Ground Type Ⅱ. The schematic diagram of the steel arch bridge and cross-section of the main component of the steel arch bridge are shown as Fig. 1, Fig. 2 and Fig. 3, respectively.



(a) Top view of main girder

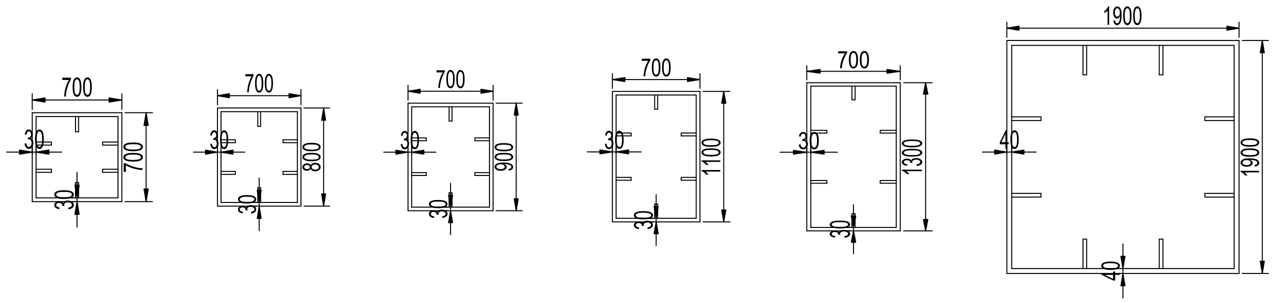


(b) Elevation of arch bridge



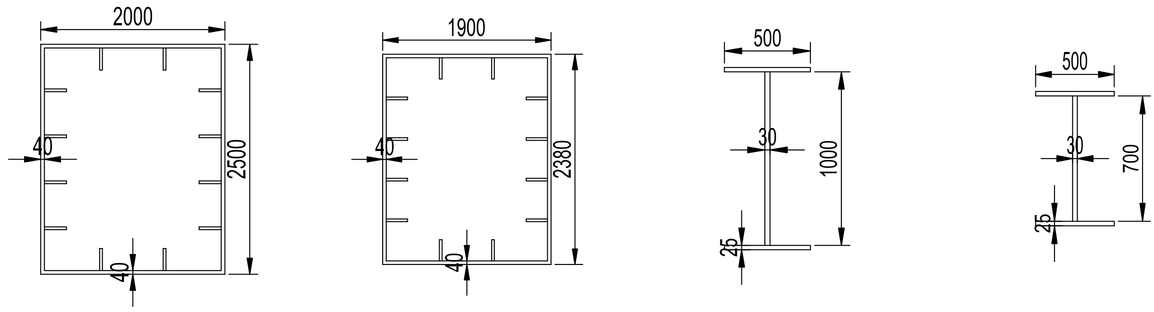
(c) Top view of arch rib

Fig.1 - The schematic diagram of the steel arch bridge



(a) 1 #column (b) 2#column (c) 3#column (d) 4#column (e) 5#column (f) side pier

Fig.2 - The cross-section of the column and side pier



(a) arch rib (b) main girder (c) cross brace (d) diagonal brace

Fig.3 - The cross-section of the main component

2.2 Establishment of FE model

A 3-D FE model of the deck steel arch bridge is established by the finite element software ABAQUS package, nonlinear dynamic time-history analysis are performed. In this study, effect of vertical ground motion on seismic performance is considered. The shell element (S4R) is used to simulate bridge deck. Beam element (B31) is used to simulate main girder, arch rib, side pier and column on the arch[5]. The inner lean angle of arch rib is 0°, 4°, 8°, 12° . The FE model of arch bridge is shown as Fig. 4, and the boundary conditions are show as Table 1.

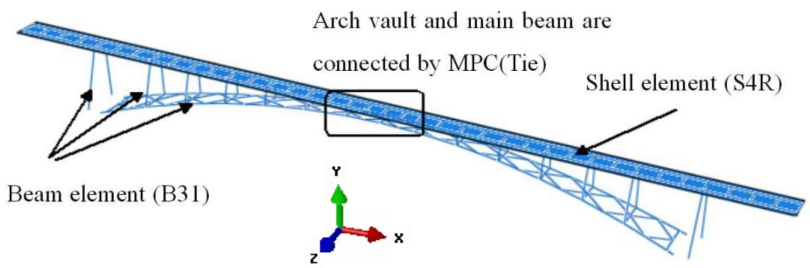


Fig.4 - Finite element model of the deck steel arch bridge

Table 1 - Boundary condition of FE Model

Position	Longitudinal(X)	Vertical(Y)	Transverse(Z)	UR1	UR2	UR3
Upper of main beam	Free	Fixed	Fixed	Free	Free	Free
Lower of side pier	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed
Arch foot	Fixed	Fixed	Fixed	Free	Free	Free

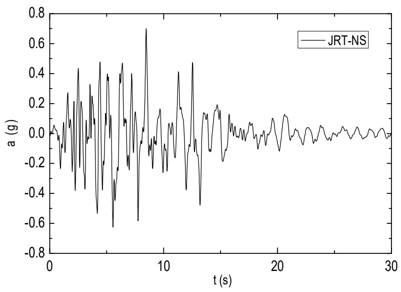
2.3 Material properties

According to Chinese standards, the arch rib, main girder, side pier and diagonal brace are made of Q345 steel material, the column and cross brace are made of Q235 steel material, the bridge deck is made of C50 concrete.

2.4 Ground motion

The JRT-NS ground motion which recorded in 1995 Kobe earthquake are inputted in this paper to the influence of inner lean angle on seismic performance of steel arch bridge, as shown as Fig. 5. It can be seen that the peak acceleration of JRT-NS is 0.7g.

The modified Newmark-β direct integration method is used for the elasto-plastic time-history analysis . The maximum time step is Δt=0.01s. The damping adopts Rayleigh damping. According to the regulations of the code, the damping ratio is 0.02.



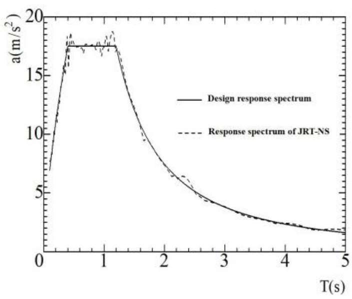


Fig.5 - Input earthquake wave　　Fig.6 - Comparison of seismic response and design spectrum

The acceleration response spectrum of JRT-NS wave is compared with the standard design response spectrum as shown in Fig. 6. It can be seen from the figure that the actual response spectrum of JRT-NS wave is in good agreement with the standard design response spectrum of intensity, which further proves rationality of the selection of ground motion.

2.5 key-section selection

In this study, the ①arch vault section, ②1/4 arch span section and ③arch foot section are selection as key section for investigating seismic performance of arch bridge(see Fig.7).

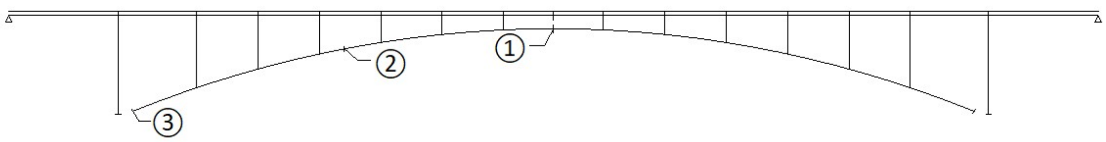


Fig.7 - Arch bridge key section

3. Influence of inner lean angle on seismic performance

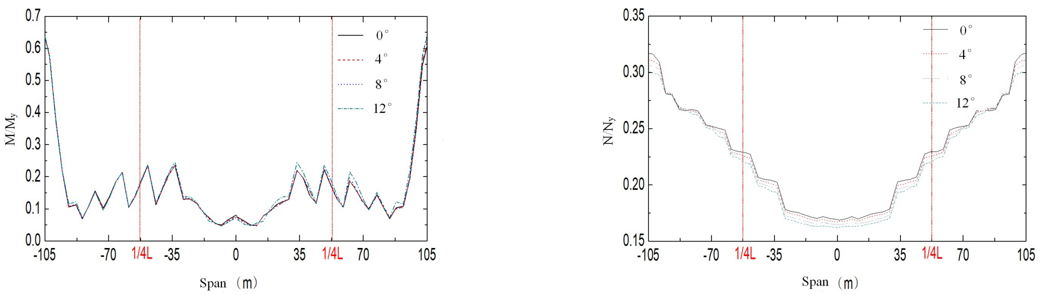
3.1 Longitudinal seismic responsive

Figure 8 shows the internal force envelope curve of the deck steel arch bridge with different inner lean angle under JRT-NS wave along longitudinal direction, where X-axis represents the span and Y-axis represents the non-dimensional internal force. The peak seismic response of key section of the steel arch bridge under longitudinal ground motion are shown in Table 2.

Table 2 - Seismic response of arch bridge under seismic wave

Arch bridge		Longitudinal ground motion			Transverse ground motion		
inner lean angle	Section position	Displacem -ent/m	Force/ N/N_y	Moment/ M/M_y	Displacem -ent/m	Force/ N/N_y	Moment/ M/M_y
	Arch vault	0.021	0.169	0.080	0.885	0.376	0.100
0°	1/4 arch span	0.036	0.229	0.172	0.603	0.314	0.114
	Arch foot	0	0.317	0.634	0	1.168	0.421
	Arch vault	0.021	0.167	0.078	0.837	0.304	0.079
4°	1/4 arch span	0.036	0.227	0.171	0.561	0.391	0.138
	Arch foot	0	0.311	0.634	0	1.272	0.716
	Arch vault	0.020	0.164	0.074	0.801	0.408	0.102
8°	1/4 arch span	0.036	0.225	0.172	0.519	0.615	0.295
	Arch foot	0	0.306	0.635	0	1.322	1.237
	Arch vault	0.019	0.167	0.065	0.740	0.345	0.086
12°	1/4 arch span	0.029	0.223	0.177	0.440	0.602	0.229
	Arch foot	0	0.300	0.639	0	1.318	0.772

It can be seen from figure 8 that the internal force response of arch rib changes in the same trend with different inner lean angle, and the internal force response curve is symmetrical along the mid-span. Comparing the moment response of the arch rib of arch bridges with different inner lean angle, the change of inner lean angle has little effect on moment response(see Fig.8-(a)). The axial force of the arch rib decreases with the increase of the inner lean angle, but the difference is not significant under longitudinal ground motion(see Fig. 8-(b)).

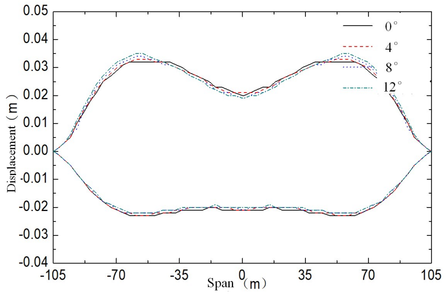


(a) Moment envelope curve

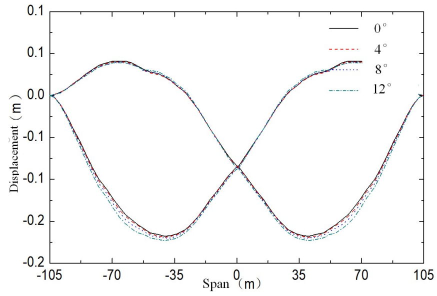
(b) Axial envelope curve

Fig.8 - Internal force envelope diagram of arch rib under longitudinal seismic wave

Figure 9 shows the displacement envelope curve of the deck steel arch bridge with different inner lean angle under JRT-NS wave along longitudinal direction, from which it can be seen that the displacement in longitudinal and vertical of arch rib is the largest at 1/4 arch span, and displacement obvious decreases in the position of arch vault. The displacement of arch rib in longitudinal direction is less affected by the change of inner lean angle.



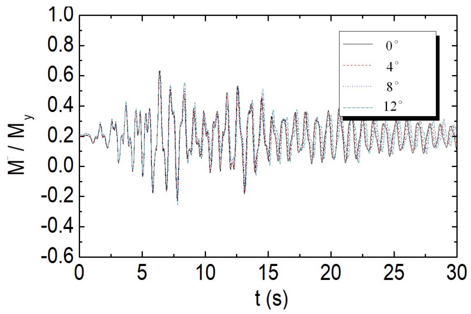
(a) Displacement in longitudinal direction



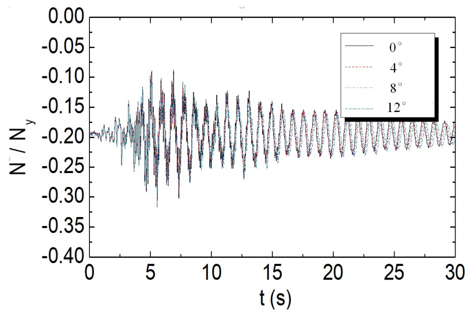
(b) Displacement in vertical direction

Fig.9 - Displacement envelope diagram of arch rib under longitudinal seismic wave

Figure 10 shows the time history curve of moment and axial force at arch foot of the deck steel arch bridge with different inner lean angle. The moment at arch foot reaches the maximum in 6.3s, which is 0.65 times of the yield moment. The maximum axial force at the arch foot is 0.32 times of the yield axial force at 5.4s, which indicated that the arch foot is in elastic state.



(a) Moment of arch foot



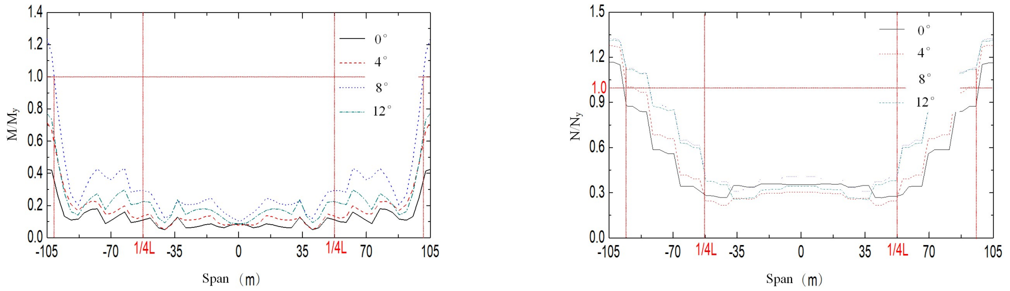
(b) Axial of arch foot

Fig.10 - Internal force time history curve at arch foot of the deck steel arch bridge

3.2 Transverse seismic responsive

Figure 11 shows the internal force envelope curve of the deck steel arch bridge with different inner lean angle under JRT-NS wave along transverse direction, where X-axis represents the span and Y-axis represents the non-dimensional internal force. The peak seismic response of arch bridge under transverse ground motion with different inner lean angle are shown as Table 2.

Among the arch bridges with different inner lean angle, the in-plane moment of the arch rib increases gradually with the increase of inner lean angle, reaches the maximum when the inner lean angle is 8° and begins to decrease when the inner lean angle is more than 8°. The moment at the arch foot is much larger than that at other positions of the arch rib(see Fig. 11-(a)). The maximum axial force of the arch bridge appears at arch foot. Comparing the axial force of arch bridge with different inner lean angle, it can be found that the axial force increase obviously with the increase of the inner lean angle. When the inner lean angle increase from the 4° to 8°, the axial force of the 1/4 arch span increase the most(see Fig. 11-(b)).



(a) Moment envelope curve (b) Axial force envelope curve

Fig.11 - Internal force envelope diagram of arch rib

Figure 12 shows the displacement envelope curve of the deck steel arch bridge with different inner lean angle under JRT-NS wave along transverse direction. The displacement in transverse direction of arch vault is larger than other sections of arch rib. With the increase of the inner lean angle, the negative displacement of the arch vault decreases and the positive displacement fist decrease and then increase. Among the arch bridge analyzed, the negative displacement of the arch vault reaches the minimum value when the inner lean angle is 12°, and the positive displacement reaches the minimum value when the inner lean angle is 4°.

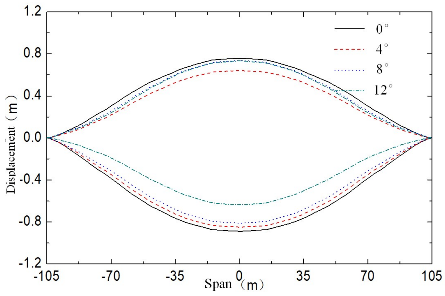
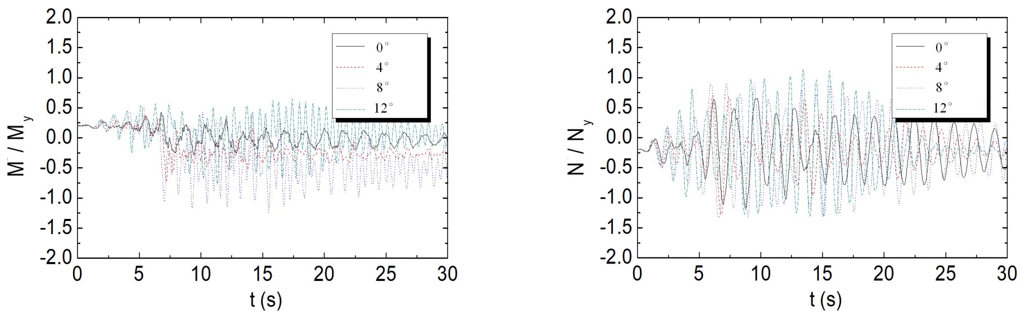


Fig.12 - Displacement envelope diagram of arch rib

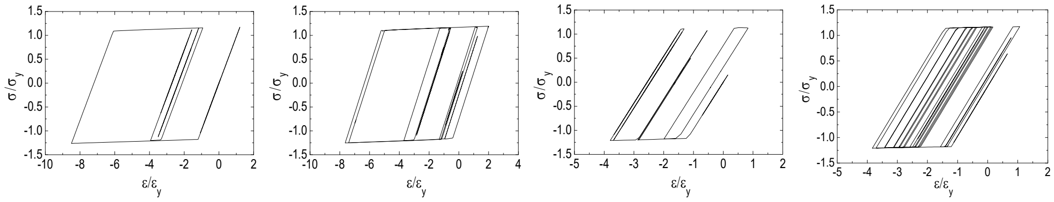
Figure 13 shows the time history curve of moment and axial force of the deck steel arch bridge with different inner lean angle under JRT-NS wave along transverse direction. It can be seen from the figure that the moment of the arch foot reaches the maximum in 9.3s and axial force reaches the maximum in 14.4s. The moment and axial force at the arch foot of bridge both exceed the yield force and enter the yield state.



(a) Moment at arch foot (b) Axial force at arch foot

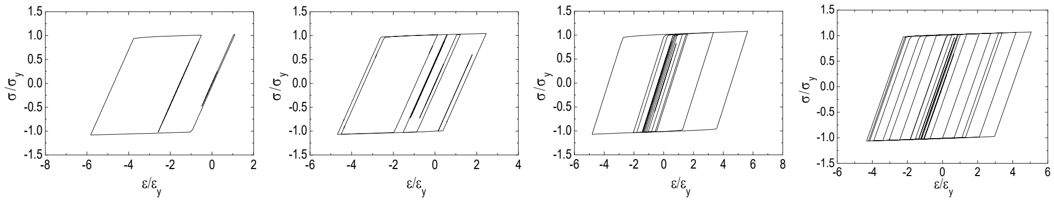
Fig.13 - Internal force time history curve of arch

Figure 14 and figure 15 show the stress-strain hysteresis responsive curves of components of arch bridges under transverse ground motion. Under the transverse ground motion, the cross-brace of arch bridge and the arch foot reach yield state.



(a) 0° (b) 4° (c) 8° (d) 12°

Fig.14 - Stress-strain hysteresis responsive curve at the cross-brace



(a) 0° (b) 4° (c) 8° (d) 12°

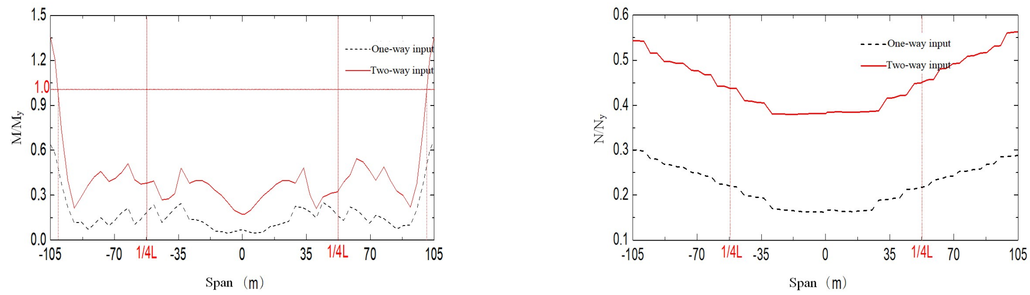
Fig.15 - Stress-strain hysteresis responsive curve at the arch foot

4. Influence of vertical ground motion on seismic performance

4.1 Longitudinal+vertical seismic response

Figure 16 shows the internal force envelope curve of the arch bridge under JRT-NS ground motion in longitudinal+vertical direction, where the two-way input refers to the results of longitudinal+vertical seismic response and one-way input refers to the results of longitudinal seismic response.

Under the two-way input, the moment of arch rib is significantly larger than that of one way input, in which the position of arch foot increases by more than one time, reaching the 1.35 times of yield moment, while the arch rib is still in elastic state under one-way input. At arch foot, the axial force of two-way input nearly doubled compared with one-way input, while in the position of arch vault, the axial force increased by 134.8%. So, it can be found that the vertical ground motion has a great influence on the internal force of arch rib of the arch bridge.

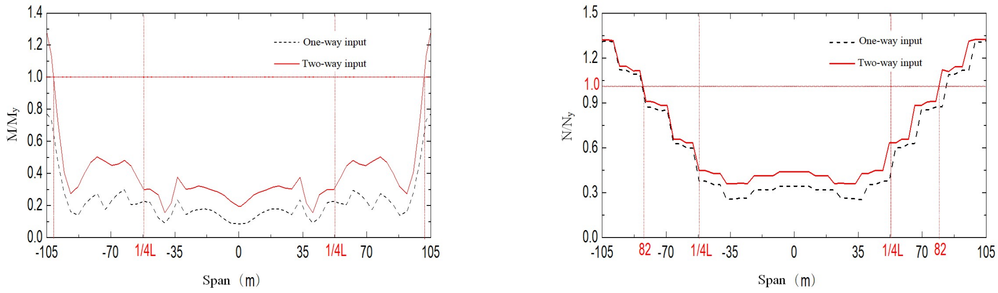


(a) Moment envelope curve (b) Axial force envelope curve

Fig.16 – Internal force envelope diagram of arch rib

4.2 Transverse+vertical seismic response

Figure 17 shows the internal force envelope curve of the arch bridge under JRT-NS ground motion in transverse+vertical direction. The moment of arch rib increases obviously under the two-way input. For the axial force, the difference between the two-way input and one-way input is very small at arch foot. At the position of 1/4 arch span and arch vault, the axial force of two-way input increases slightly compared with that of one-way input, and the increase amplitude is 16.8% and 27.9%, respectively. It can be seen that the vertical ground motion has an effect on the axial force of the arch vault and 1/4 arch span of arch bridge, but has little effect on the axial force of the arch foot.



(a) Moment envelope curve

(b) Axial force envelope curve

Fig.17 – Internal force envelope diagram of arch rib

5. Conclusion

(1) Under transverse ground motion, the responsive maximum displacement is the arch bridge with inner lean angle 0° and the responsive minimum displacement is the arch bridge with inner lean angle 12° among the four arch bridges. Increasing the inner lean angle can improve the transverse stiffness of the arch bridge. The in-plane moment and axial force of the arch rib increase first and then decrease with the increase of inner lean angle, and the responsive maximum axial force is the arch bridge with the inner lean angle 8°.

(2) Under longitudinal ground motion, the influence of inner lean angle of the arch rib on axial force and moment of arch rib is not obvious. The responsive displacement of arch rib in longitudinal and vertical direction reaches the maximum at 1/4 arch span position, and the responsive displacement is less affected by the change of inner lean angle.

(3) The vertical ground motion has a great effect on the responsive axial force and moment response of arch bridge. The responsive axial force and the responsive moment under the longitudinal+vertical ground motion are significantly larger than those under the longitudinal ground motion. Under the transverse+vertical ground motion, the responsive moment of arch rib is greater than that under transverse ground motion, and the responsive axial force increases slightly at arch vault and 1/4 arch span.

6. References

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